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Influence of aggregate granulometry on air content in concrete mixture and freezing - thawing resistance of concrete

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Abstract

Concrete frost resistance is one of the main factors that effects its durability. This is particularly important in the harsh climate regions where the water in concrete pores gets multiple freeze-thaw cycles. Concrete frost resistance can be increased by changing the coarse aggregate content by volume in the concrete mixture, as it is changing ~~and~~ concrete porosity. It was found that coarse aggregate volume concentration increase has a negative effect on predicted freezing - thawing resistance of concrete. It was found the correlation between a closed porosity of concrete, coarse aggregate volumetric concentration, air content in the concrete mixture and the predicted frost resistance of concrete. After statistical processing of test results it was found significant dependencies between coarse aggregate volumetric concentration in concrete, its closed porosity and predicted concrete freezing – thawing resistance and durability of concrete.

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Keywords: concrete, aggregate, durability, freezing - thawing resistance, porosity, air content, absopbtion.

Introduction

Concrete, as it is known today, is a construction material consisting of primarily rocks of limited maximum size that meet certain characteristics related to their mechanical, chemical, and granulometric properties and which are merged by a binding paste formed by a binder (cement) and water." [1]

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Hardened cement paste, cement mortar or concrete is porous materials which in can penetrate gas or liquids. Materials can be influenced by porosity in different ways. Total porosity volume, size of pores, pore distribution in material, bigest pore size, shape and bond between, have influence to concrete strength and elasticity. Durability of concrete depends on freezig - thawing resistance and can be controled by different pore volume and spacing between them [2;3].

Cement stone strength and durability depend ragely on the input of cement and water and cement and water ratio (W/C). Increasing this ratio concrete quality decreasing [4]. Pores existing in cement stone can be divided into three main groups: capillary pores, pores of the gell, air pores [5].

Capillary pores in cement stone arise after evaporation of water excess from the production of concrete mix. In most cases, the production of mixtures provide more water than necessary to occur chemical reactions. Capillary pores are open and easy fill up with water. The ammount of water in cement stone is main factor causing the destructive effects of freezing. The higher capillary pore volume and size, the lower is resistance to freezing [4]. Ammount of capillary pores in hardened cement stone depends on W/C ratio [6;7].

T. C. Powers opinion, the cement stone freezing - thawing resistance is increasing, reducing in W/C ratio 0,4 and less [8]. R. Feldman found that water content in capillary pores completely frozen when temperature drops below –13 °C and the temperature interval of 0 °C to –13 °C is ice formation in capillary pores period [9].

Pores of the gel does not effect the freezing - thawing resistance of cement stone because they are very small. The size is 1.5 to 2.0 nm [4;6;10;11]. Gel pores have no significant effect on concrete strength and conductivity because they are very small and have no free water [13].

Closed/air pores are forming by including air from environment and hardening cement stone contraction. Air inclusion promotes some special additives and contraction occurs naturally. Included air pores and contraction pores form closed porosity which improves freeze resistance. Air pores formated by included air, unlike capillary pores, increasing conglomerate freezing - thawing resistance. In water absorption air pores remains dry because they are closed. Air pore fineness, is another feature that infuences the cement stone frost resistance. Cement with the same quantity of air, the smaller the air pores are, more numerous and smaller distances between them. In this case water, infulenced with ice pressure have to penetrate to the air pore. When the average distance between the air pores are less 200 μm cement stone is frost resistant [4;6;13;14].

Main decay, cracking and reason for the crumbling is that the water which turn into ice, the volume increases. Water density is 1 g/cm^3, adn the ice is 0,917 g/cm^3. Ice holds 9 % greater volume than water. Ice crystals depressing hardened cement stone pore and capillary walls, expanding the product and may disrupt it [15;16].

Cement stone degradation due to frost is the most common cement stone products destruction in case. The cyclically-cooled and reheated, the water saturated cement stone as well as other mineral solid body can be degraded [17].

There are concrete forst resistance criteria K_F – it is a closed porosity of P_u (included air + contraction pores) and open porosity P_a (capillary pores) ratio: $K_F = P_u / 0{,}09\ P_a$. Air critical mass is about 3 %. Thus, if the concrete or mortar mixture compacted in semi finished product included air is more than 3 % it can be expected that the product will be frost reisistant. The required amount of entrained air further depends upon the composition of the conrete mix, cement content, W/C ratio, aggregate size, distribution of entrained air and pore size and so on [18].

Cement stone frost resistance reduces the open and capillarie pores, which are formed be evaporation of the free water in cement stone. Such capillary pores and amount of them depend on the W/C ratio. The more water was added in to cement stone mixture, the more remains unbound water, after evaporation formed open porosity [17].

D. Nagrockienė and others, used different coarse aggregate concrentations. They found the dependencies between coarse aggregate volumetric concentration and air void in hardened concrete. The concrete with bigger ammount of coarse aggregate have lowest closed porosity and lowest freezing-thawing resistance [19].

Of the coarse aggregate and hod interoperability is currently no consensus. Traditinional opinion argues that the total aggregate surface area should be minimal, it means that concrete mixtures should be designed with the maximum amount of coarse aggregate. Gumuliauskas *et. al.* indicates that the coarse aggregate in the mixtures should be not at a maximum [20]. G. Skripkiūnas and others believes that the focus in designing strong concrete is to the distribution of coarse aggregate in concrete and stress concrentation around coarse aggregates [21].

M. Daukšys with others conducted the research to determine a predicted frost resistance of concrete by concrete porosity parameters. In research as fine aggregate used 0/1; 0/2 and 0/4 sand and coarse aggregate 4/16 fraction gravel. The concrete samples acording to the volumetric cooling forecasted freezing and thawing cycles it appears that only a fine grained concete (obtained without the use of coease aggregate) withstood the expected number of cycles. Concrete with coarse aggregate according to its porosity parameters set nuber of cycles did not withstood [22].

Materials and test methods

The concrete mix was made of water, cement, sand and coarse aggregate gravel and crushed gravel. Concrete compositions differed by the amount of gravel and sand. Portland cement produced in AB "Akmenės cementas", specimens were made of CEM I 42.5 N class Portland cement complying with LST EN 197-1:2000 standard requirements. Gravel and crushed gravel was used 4/16 mm fraction, sand 0/4 mm.

Table 1. Properties of sand 0/4, gravel 4/16 and crushed gravel 4/16.

	Sand	Gravel	Crushed gravel
Property	value	value	value
Density, kg/m^3	2620	2600	2610
Bulk density, kg/m^3:			
normal state	1660	1525	1410
compacted state	1875	1725	1600
Porosity, %:			
normal state	36.6	41.3	46
compacted state	28.4	33.7	38.6
Coarseness module	2.94		

Two different concrete composition with different fine aggregate and coarse aggregate concentrations where investigated. First one was made of gravel, sand, water and cement, second one: crushed gravel, sand water and cement. Concrete composition and technological properties are presented in Tables 2, 3.

Table 2. Concrete composition and technological properties with gravel.

		Materials for 1m^3 concrete, kg				Concrete mix		
No.	φ_{st}	Cement	Gravel	Sand	Water	Density kg/m3	Air content, %	Slump, cm
1.1	0.52	368	1356	516	187	2427	0	3.5
1.2	0.48	367	1248	615	187	2417	0.24	4.5
1.3	0.44	367	1143	709	187	2406	0.61	4
1.4	0.4	368	1044	809	184	2405	0.79	3.2
1.5	0.36	361	927	911	182	2381	1.73	2.8
1.6	0.31	360	815	1020	182	2377	1.82	1.8
1.7	0.23	358	611	1207	181	2357	2.53	0.8
1.8	0.16	356	404	1396	180	2336	3.28	0
1.9	0.08	349	197	1558	177	2281	5.4	0
1.10	0	347	0	1751	178	2276	5.43	0

Table 3. Concrete composition and technological properties with crushed gravel.

		Materials for 1m^3 concrete, kg				Concrete mix		
No.	φ_{st}	Cement	Crushed gravel	Sand	Water	Density kg/m^3	Air content, %	Slump, cm

2.1	0.54	355	1418	449	193	2415	0.03	16
2.2	0.47	356	1221	639	193	2409	0.13	13.5
2.3	0.43	355	1114	744	192	2405	0.27	11.5
2.4	0.39	353	1010	844	192	2399	0.41	9
2.5	0.34	350	899	937	190	2376	1.31	7
2.6	0.3	346	791	1030	188	2355	2.14	3.5
2.7	0.22	340	583	1209	185	2317	3.58	1.5
2.8	0.15	345	394	1356	187	2282	4.68	0.5
2.9	0.08	345	197	1509	187	2238	6.2	0
2.10	0	347	0	1663	188	2198	7.52	0

The concentration of coarse aggregate φ_{st} in concrete was derived from the equation:

$$\varphi_{st} = \frac{S_t}{\rho_{st}} \tag{1}$$

where: S_t - coarse aggregate content in concrete; ρ_{st} – coarse aggregate density.

The total porosity of concrete was determined by concrete density, whereas open porosity was determined by the total water saturation. Concrete slump and density were tested according to EN 12350-2, EN 12350-6. Entrained air content was calculated from fresh concrete density and constituent materials densities:

$$P = \left[1 - \left(\frac{C}{\rho_c} + \frac{S_m}{\rho_{Sm}} + \frac{S_t}{\rho_{St}\left(1 + \frac{W_{St}}{100}\right)} + \frac{V - \frac{W_{St} \cdot S_t}{100}}{\rho_v}\right)\right]100 \tag{2}$$

where: C, S_m , S_t, V – cement, sand, coarse aggregate and water contents in concrete; ρ_c, ρ_{sm}, ρ_{st}, ρ_v – cement, sand, coarse aggregate and water densities.

Concrete specimens were made 100 x 100 x 100 mm, which were compacted on laboratory vibration table. After one day curing in forms specimens were removed from formwork and cured 27 days in water. Later, these samples were split into cubes 50x50x50 mm for water absorbtion kinetics, density and specific gravity determination tests. Specific gravity of concrete was determined by pycnometer method.

All samples were tested at the same time, so the environmental impact of all was the same.

Experimental results

Tested specimens kinetics of water absorption is presented in figures 1 and 2. Highest water absorption was reached for specimens without coarse aggregate. Increasing coarse aggregate volume concentration water absorption decreased. Water absorption kinetics in first one hour shown that the specimens with gravel coarse aggregate reached 86 % whereas crushed gravel coarse aggregate reached 72 % of total absorption.

Test results of the porosity of concrete specimens with different amount of coarse aggregate concentration shown in figs. 3 and 4. Increasing concentration of coarse aggregate the amount of closed porosity is decreasing. When φ_{st} reaches 0.54 the concrete almost have no closed pores and it is less frost resistance.

How we can see from data shown in figures 3 and 4 using crushed gravel coarse aggregate total porosity of concrete is higher than using gravel coarse aggregate. Influence of absorption by increasing coarse aggregate concentration have a larger impact to concrete with crushed gravel coarse aggregate. The total porosity is decreasing from 19.74 % with 0 coarse aggregate to 13.33 % with φ_{st} - 0.54 than using gravel coarse aggregate the total porosity with φ_{st}-0 is 16.95 and φ_{st}-0.52 is 10.37 %. We can see that crushed gravel have a more significant effect to porosity parametersand air content changes than gravel coarse aggregate.

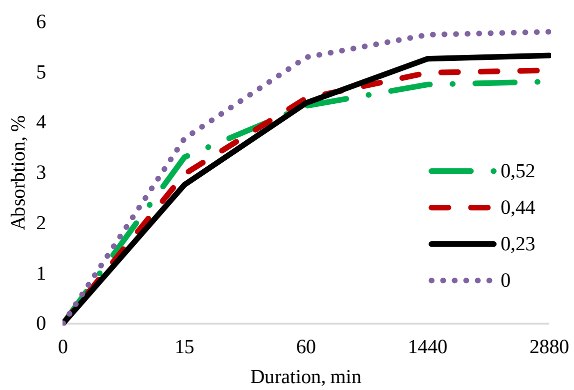

Fig. 1. Function of absorption and duration with gravel coarse aggregate.

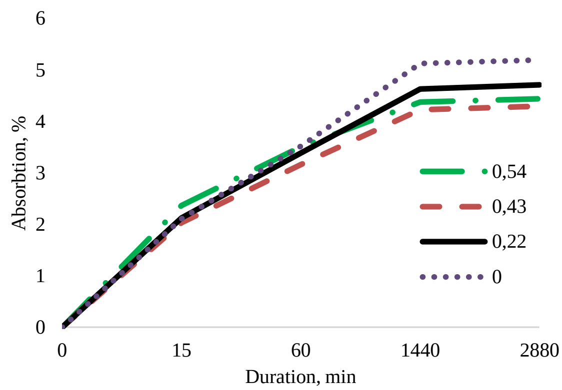

Fig 2. Function of absorption and duration with crushed gravel coarse aggregate.

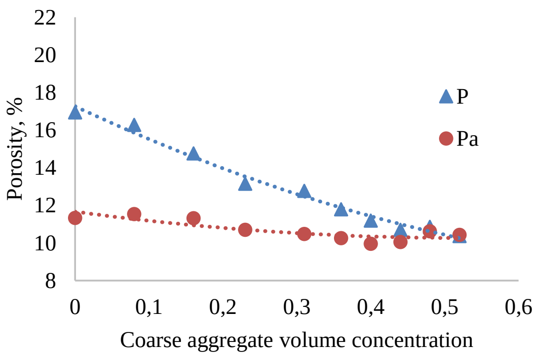

Fig. 3. Function of porosity and coarse aggregate volume concentration (gravel).

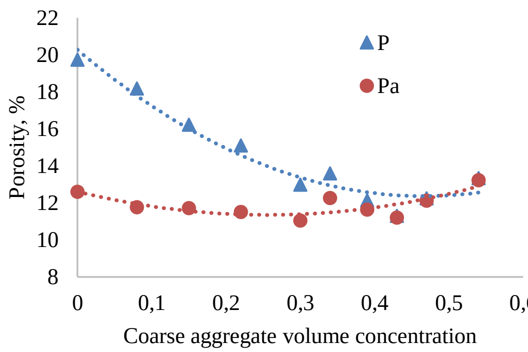

Fig. 4. Function of porosity and coarse aggregate volume concentration (crushed gravel)..

Increasing coarse aggregate volume concentration the total porosity is reducing while open porosity almost remain constant.

Statistical processing of test results by using a linear function model between air content in concrete mixes and closed porosity with gravel and crushed gravel coarse aggregate (fig. 5). Using gravel coarse aggregate the correlation of the function r=0.987 and determination coefficient R^2= 0.974. Processing empirical data was produced closed porosity prediction equation for concrete:

$$P_u = 0.965 \cdot A \tag{3}$$

Where: P_u is closed concrete porosity, %; A is entrained air content in concrete mix, %.

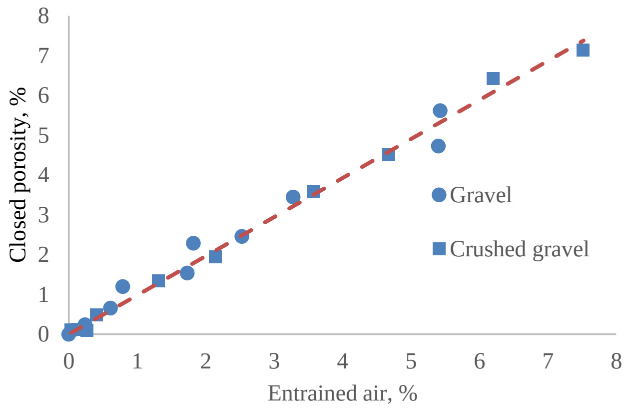

Fig. 5. Function of closed porosity and air content in concrete mix with gravel and crushed gravel coarse aggregate.

The work revealed the significantly correlation between closed porosity and air content in concrete using crushed gravel coarse aggregate which correlation coefficient r=0.997, determination coefficient R^2= 0.996. It can be concluded that is no difference between using gravel or crushed gravel coarse aggregate.

Relationship between coarse aggregate volume concentration and frost resistance criteria K_F is shown in fig. 6. Statistical processing test results with gravel have been found correlation coefficient r=0.993, determination coefficient R^2= 0.98. With crushed gravel the correlation coefficient r=0.974, determination coefficient R^2= 0.979. Test results scattering is shown in figure 6. Using both coarse aggregate types frost resistance criteria (K_F) can be predicted with linear function:

$$K_F = 5.88 - 12 \cdot \varphi_{st} \tag{4}$$

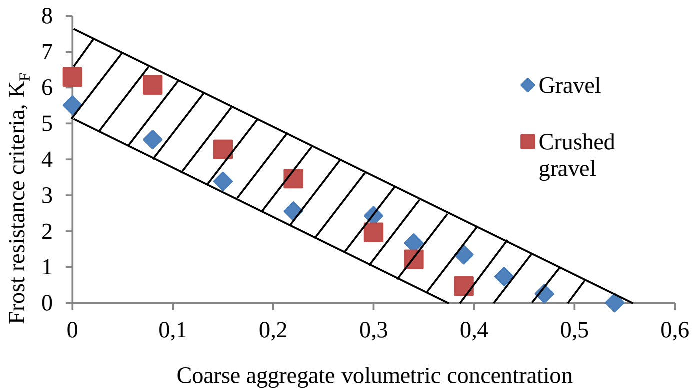

Fig. 6. Function of frost resistance criteria and different coarse aggregate volume concentration.

Test results have shown that frost resistance factor depends on closed porosity of concrete by linear function. Statistical processing of test results by using linear function model produced a function of closed porosity and frost resistance factor for concrete. Have been found correlation coefficient r=0.998, determination coefficient R^2= 0.997. Frost resistance factor can be calculated knowing closed concrete porosity or entrained air content in concrete mix by equation:

$$K_F = 0.96 \cdot P_u + 0.1 = 0.93 \cdot A \quad (5)$$

The equation valid for concrete with about 300 l cement paste content or about 350 kg cement for 1m^3 concrete mix with plastic consistency.

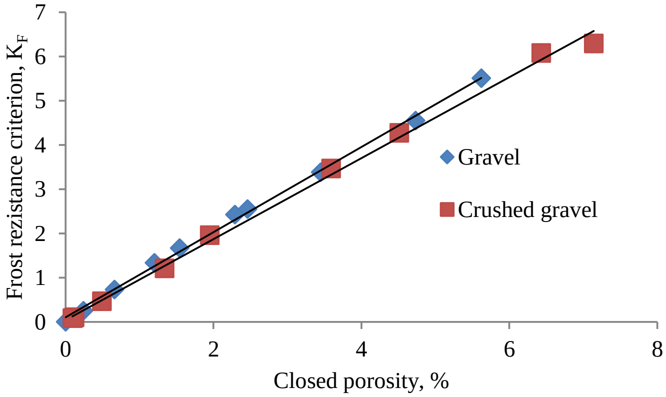

Fig. 7. Function of frost resistance criterion and closed porosity of concrete.

Where is significant dependence between coarse aggregate volume concentration in concrete mix and frost resistance factor, less is used coarse aggregate concentration the higher is frost resistance criterion of concrete.

It was found that coarse aggregate particle form had no significant impact on the quantity of air in concrete mixture and its freezing - thawing resistance. Coarse aggregate concentration determine the concrete frost resistance criterion K_F, which can be predicted from water absorption rate of hardened concrete or entrained air content in concrete mixture.

Conclusions

1. Coarse aggregate particle form have no significant impact on the quantity of entrained air in concrete mixture therefore and its freezing - thawing resistance.
2. Coarse aggregate concentration in concrete determine the concrete freezing - thawing resistance criterion K_F, which can by predicted from water absorption rate of hardened concrete or entrained air content in concrete mixture.
3. After statistical processing of test results it was found significant dependencies between coarse aggregate volumetric concentration in concrete, its closed porosity and predicted concrete freezing – thawing resistance and durability of concrete.

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